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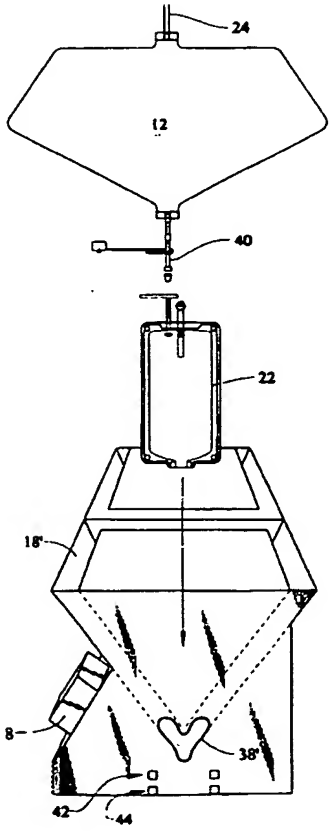
(54) Title: RED CELL SEDIMENTATION SYSTEM

(57) Abstract

An automated system for separating red blood cells from fluids by gravity utilizes a process bag (12) into which the red blood cells and other fluids are mixed with starch. The bag (12) is held at an angle that promotes rapid settling of red blood cells that have agglomerated by the action of the starch (i.e. formation of rouleaux). The bag (12) is held at the proper angle by a holder (4) that includes a slot (18) into which the bag (12) is placed prior to supplying it with fluids and red blood cells. The slot (18) is arranged such that the bag (12) is symmetrically arranged about an axis whereby the red blood cells settle to a common point for discharge. The system includes a control circuit (52) that automates supply of the red blood cells and fluids to the bag (12) and discharge of the separated red blood cells from the bag (12).



RED CELL SEDIMENTATION SYSTEM

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of provisional patent application serial number 60/076,671.

TECHNICAL FIELD

This invention relates to the art of methods and apparatus for separating red blood cells from liquids, particularly those used for washing red blood cells in salvaged blood, but also including plasma and other fluids.

BACKGROUND

Separation of red blood cells from plasma or other fluids is known. For example it is known to collect shed blood during surgery, separate the red blood cells from the collected fluids, and return the red blood cells to the patient. The separated fluids are then discarded. Often, additional fluids are added to the collected blood to "wash" the red blood cells. The original plasma and the added fluids are separated from the red blood cells during a process known in the art "cell washing."

The importance of fast and easy cell washing has increased with the development of surgical methods that rely on salvaging blood from a patient and returning that blood to the patient instead of blood from donors. Prior cell washing systems have relied primarily on centrifugation, which is complicated and expensive.

Systems that utilize sedimentation to separate red blood cells from fluids have been proposed, but these are complicated and ineffective.

SUMMARY OF THE INVENTION

In accordance with the invention, an automated system for separating red blood cells from plasma and other fluids relies upon sedimentation of the red blood cells under the forces of gravity. The invention, however, can be applied to a system where the forces on the red blood cells are increased, as by centrifugation.

According to the invention, a bag containing fluid in which the red blood cells are suspended is oriented to allow the red blood cells to separate from the fluid by sedimentation. As this sedimentation proceeds a "meniscus" forms. This meniscus is the boundary between a layer of the fluid having an increased concentration of red blood cells and a layer having a reduced concentration of red blood cells. As the sedimentation continues, the meniscus moves downward, and the position of the meniscus is monitored. In the preferred embodiment, a series of light emitting diodes (LED) is arranged on one side of the bag containing the fluid and a matching series of photocells is arranged on the opposite side. Thus, as the meniscus moves past a LED-photocell pair, the intensity of light (e.g., infrared) detected by the photocell will increase. The signals from the photocells are provided to a programmable logic controller (PLC) for processing.

In the preferred embodiment, the fluid containing the cells to be separated is supplied with a sterile fluid that promotes a rouleaux of the red blood cells, the roll-like configuration the red blood cells assume when they group together. A preferred such fluid is hydroxy-ethyl starch, which is believed to form a bridge between charged red

blood cells to weaken the repulsion among the cells and allow them to agglomerate, in the rouleaux process. The rouleaux of red blood cells settles under the force of gravity much faster that do individual cells, a phenomenon explained by known laws of fluid dynamics.

The blood and sterile washing fluid containing starch are collected by pumping them into a process bag. In the preferred embodiment, a fluid line (e.g., a flexible tubing) from a source of salvaged blood is passed through one peristaltic pump, and a fluid line from a source of starch is passed through a second peristaltic pump. The source of salvaged blood is preferably the collection reservoir of the product sold by Harvest Technologies under the trademark "Bloodstream" but other sources of blood may clearly be employed. Further, other types of pumps, such as diaphragm or piston pumps, may be used in place of the peristaltic pumps.

The process bag is placed in a holder that supports the bag such that all parts of the bag are oriented at about 40° to about 70° with respect to the horizontal and taper to a common output . The preferred orientation is about 55°. One geometric form for the holder that provides these features is that of a cone. In the preferred embodiment, however, the process bag is held in this orientation and configuration by placing it an inclined channel, which is formed between an inverted, pyramidal cavity and a matching pyramidal top, the top being spaced from the lower surface of the pyramidal cavity by a distance of less than about 2 inches and preferably about 1.15 inch. Because the bag is held in this slot, it is constrained to the 1.15 inch thickness. The slot formed by the pyramidal arrangement of the preferred embodiment is triangular and, thus, naturally directs the collected red blood cells toward a common point at the vertex, much like the

action of a funnel. Further, the vertexes of the several triangular faces are coincident, directing all of the red blood cells to a common point.

The LED-photocell pairs for measuring the position or movement of the meniscus are mounted on surfaces of the holder such that the LED's and the photocells are on opposite sides of the channel and, hence, opposite sides of the process bag held in the channel.

Because the thickness of the bag is constrained to the 1.15 inch thickness of the channel, the maximum vertical distance an agglomeration of red blood cells must fall before encountering the lower wall of the holder is about 1.75 inch. This means that all of the agglomerations of red blood cells accumulate on the lower surface of the holder quickly, and they then slide down that surface easily to accumulate at the bottom of the process bag. The triangular shape of the bag, as constrained by the slot, naturally concentrates the agglomerations of red blood cells to the outlet of the bag located at the tip of the pyramid

Data is collected at several points in the system and is provided to a control element, such as a PLC (programmable logic controller), from the various elements of the system. The PLC is programmed to control the supply of recovered blood and starch or other washing fluids to the process bag, the discharge of recovered red blood cells from the process bag, and other aspects of the system. The peristaltic pumps are controlled to transfer prescribed amounts of the fluid and blood to the process bag. Sensors, which may be optical and are preferably acoustical, are provided adjacent the tubes leading from the pumps to determine whether fluid is indeed present in the tubes, and, in some instances, to determine the hematocrit of the fluids. The LED-optical

sensor pairs in the process bag holder provide electronic signals indicative of the location and movement of the meniscus.

The data supplied by the various sensors may be used in any of several processes automate control of the system whereby the system is easy to set up and use. In the preferred embodiment, the signals are processed to determine whether a proper separation has taken place. Data representing the volume of blood transferred to the process bag is provided to the PLC, and the distance through which the meniscus should move in a given period of time is known empirically. For example, in many situations, movement of the meniscus to a position representing one-half the original volume in the process bag indicates that a separation warranting opening the drain valve has occurred. If the data from the sensors in the holder indicate that the meniscus has moved by that amount in the time period, the PLC knows that such a separation has taken place. The outlet valve to drain the process bag will then open to transfer the red blood cells to a bag having an integral filter for transfusion back to the patient, and that valve will remain open for a predetermined time after the meniscus has passed the lowest of the sensors in the bag holder adjacent the process bag.

The outlet line is provided with an LED-photocell sensor that detects the hematocrit of the red blood cells flowing in the outlet line from the process bag. When the hematocrit of the fluid in the output line fall to a set point or below (e.g., less than 35%), the PLC will close the outlet valve, and the draining will be complete. It is possible to open the drain valve again after a period of time determined by the PLC as a function of the blood volume remaining to be compacted. The remaining blood volume could be assessed by determining the distance between the position of the

meniscus when the valve first opened and the position of the meniscus when the valve closed.

The hematocrit sensor on the output line can also be used to sample the hematocrit of the fluid at the bottom of the process bag by periodically opening the valve for a short time. If the hematocrit is above a set point, the output valve remains open to drain the process bag.

Processing systems other than the preferred one are possible. For example the signals from the process bag sensors may be processed to determine the velocity of the meniscus, as that provides an indication of the time required to complete the separation of the red blood cells from the fluid. For example, the controller can record the time taken for the meniscus to move between two or more LED-photocell pairs, which will indicate the meniscus velocity. These times are then compared with values stored in a look-up table. A value indicating the expected time required to complete separation will be associated in the table with each set of time values, whereby the time for completion is then known as soon as a match between the measured times and stored times is made. As an alternative to the look-up table, the processor can be programmed to calculate the time for completion from a mathematical model, the data from the photocells being applied to the model.

Another way of looking at the process just described is that measurement of the meniscus velocity by the LED-photocell pairs determines the hematocrit of the fluid. Because the expected time for completion of the separation is a function of the hematocrit, determination of the hematocrit allows prediction of the time for completion.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a perspective of an apparatus in accordance with the invention.

Figure 1A is a perspective of a support and control unit of the apparatus of figure 1.

Figure 2 is a graphic layout of disposable components in accordance with the invention used with the apparatus of figure 1.

Figure 3 is a perspective of the support and control unit illustrating installation of the process bag.

Figure 4 is a schematic diagram of the red blood cell sedimentation system of figure 1.

Figure 5 is a block diagram of the control system for the system of figure 1.

DETAILED DESCRIPTION OF THE INVENTION

With reference to figure 1, a red-blood-cell-sedimentation system 2 in accordance with the invention includes a process bag support and control unit 4. The unit 4 is shown supported by a known IV pole 6, but it can be supported in a variety of places and manners. For example, the unit 4 may be placed on an IV pole carrying the noted Bloodstream system. The front face of the unit 4 has mounted thereon a first pump 8, such as a peristaltic roller pump, for withdrawing shed blood from a reservoir (not shown). The reservoir may be any known reservoir and is preferably the reservoir of the Bloodstream blood recovery system.

A second pump 10, also preferably a peristaltic pump, is mounted to the front face of the unit 4 adjacent the first pump. This second pump is provided to supply the starch to be mixed with the recovered blood as will be described in detail below.

Recovered blood is mixed with starch and supplied to a process bag 12, which is shown in figure 2. The unit 4 is designed to hold two such process bags, each bag being held in a narrow channel formed in the unit. Figure 1A is a view of the left of the unit 4 and shows the pyramidal interior structure in phantom lines. As shown in figure 1A, the unit 4 includes first outer pyramidal surfaces 14 and 14' and inner pyramidal surfaces 16 and 16'. Each of the inner and outer pyramidal surfaces comprises, respectively, three mutually-inclined triangular faces. The triangular faces of the outer surface are spaced from those of the inner surface to form the channels 18 and 18'. It will be appreciated that the left and right sides of the unit 4 are formed by vertical faces and that the faces forming the channels 18 and 18' are each inclined with respect to the horizontal at about 55°.

Figure 2 shows three disposable elements for use with the apparatus of figure 1. These are a process bag 12, a mixing Y-set 20, and a filter bag 22.

The process bag 12 is a flexible bag shaped to provide, when folded along the dotted fold lines, three triangular panels that conform to the shape of channel 18. A fill tube 24 is connected to the process bag at one end and to the mixing y-set 20 at the other. The mixing y-set comprises a first tube 26, which is intended to be connected to a bag 32 of starch, a second tube 28, which is intended for connection to a source of salvaged blood, and a mixing y-connector 30.

As illustrated in figure 2, in operation the tube 26 is fed through pump 10 and tube 28 is fed through pump 8. Fluid sensors 34, which may be optical, such as an LED-photocell combination, or of other types, such as acoustic, are placed adjacent each respective tube 26 and 28 to detect the presence or absence of fluid therein. The

sensors 34 are shown upstream of the pumps 8 and 10 but may be downstream as well. The outlet of the mixing y-connector is connected to the fill tube 24 at an interlock 36. This interlock detects the proper connection of the fill tube to the y-connector and provides a signal to the PLC. If the connection is not satisfactory, the PLC will not enable operation of the pumps 8 and 10. This ensures that fluids are not pumped if the connection to the bag is not secure.

Figure 3 illustrates the manner in which a process bag 12 and filter bag 22 are inserted into the channel 18' (figure 3 shows the right side of unit 4). The vertical face of the unit includes an opening 38' through which the drain line 40 of the process bag and the filter bag extend when the process bag 12 is fully seated in the channel 18. The channel 18 on the opposite side of the unit 4 includes an opening 38, shown in figure 1, to received the filter bag for the set received in channel 18.

After the process bag has been fully inserted, the drain line 40 is placed in a drain control valve 42, which controls the outlet from the bag 12. In the preferred embodiment, the drain control is a pinch valve that is spring loaded to be normally closed but which can be opened by energizing a solenoid that counteracts the force of the spring to release the pressure on the drain line 40. This valve can be any of several types of valves controlled by other means known in the art.

The drain line is also placed in a hematocrit sensor 44, which detects the hematocrit of the fluid exiting the process bag 12. This sensor may be an LED-photocell sensor as known in the art or similar sensors that are capable of detecting the hematocrit of the exiting fluid.

Figure 4 schematically illustrates the arrangement of the parts when the process bag is in an operative position in the channel 18 formed between the inner pyramid 16 and the outer pyramid 14. Figure 4 shows the other pyramidal surfaces 14' and 16' in phantom lines to illustrate their arrangement in the unit 4. It will be appreciated that a triangular space 46 is formed between the inner surfaces 14 and 14', which is used to house circuit boards and other electronic elements (not shown) for controlling the system.

The process bag 12 is held adjacent a set of optical sensors 48 that are placed opposite a series of light sources (e.g. LED's) to determine automatically when the red blood cells have separated from the plasma and other fluids to the desired degree. Data from the optical sensors are supplied to the PLC to determine when the separation is complete. In the preferred embodiment, there are twenty-eight sensors 48.

In operation the red blood cells are caused to agglomerate and form the rouleaux, by adding the starch mixture in the y-connector 30. In the embodiment shown, both the shed blood and the sterile starch are drawn into the bag 12 by action of the pumps 8 and 10. Alternately, a single pump is used.

The outlet valve 42 is preferably maintained in a closed condition until the desired separation between the red blood cells and the fluid has occurred, whereupon the valve is opened and the red blood cells are discharged into the filter bag 22 for eventual return to the patient. Preferably, the bag 22 includes a 40μ filter, for removing contaminates.

Applicants have discovered that the sedimentation proceeds faster when the thickness of the bag is limited to about two inches and the bag is held at an angle of about 55° to the horizontal. To achieve this configuration in a small space, the bag is may be placed in the holder shown whereby all parts of the bag are held in the desired attitude, and a minimum of space is required. Because a conical configuration is somewhat difficult to manufacture, the preferred embodiment employs the illustrated semi-pyramidal shape. Thus, a cavity having three sides with dihedral angles of 90° between each adjacent pair of sides is provided.

Figure 5 illustrates the operation of the controller 52. While this is preferably a known PLC, it may be other devices capable of providing the described functions, including microprocessors or other electronic circuits and may include mechanical elements as well. The controller 52 receives input from the photocells 48, the air sensors 34, and the hematocrit sensor 44, and controls the solenoid at 54 that is part of the drain valve 42. An optical switch (not illustrated) provides information at 56 indicating the status of the solenoid in the drain valve. The PLC also controls the pumps 8 and 10 and receives inputs from encoders associated with each of the pumps recording the operation of the pumps.

After a process bag 12 is placed in the slot 18, and the tubes 26 and 28 are fed into the pumps 10 and 8, the system operates as follows:

Priming and Mixing: The tube 26 is connected to a bag of starch, and the tube 28 is connected to a source of blood, such as the reservoir of the Bloodstream system. The tubes 26 and 28, and the y-connector are preferably supplied as a disposable article, the tube 26 having a spike for engaging the bag 32 of starch and the tube 28

having a connector for connection to the Bloodstream reservoir. The system is then activated, and the PLC causes the pumps to begin operation. The sensors 34 detect when fluid is present in the tubes 26 and 28, and the pump for the line that primes first is instructed to stop until the other line has been primed. Then the two pumps operate simultaneously to draw blood and fluid into and through the mixing y-connector. The size of the y-connector is such that turbulent mixing of the fluid and blood occurs. This continues until the starch or the blood is exhausted, the process bag is determined to be full as indicted by the pump encoder signals or the optical sensors in the unit 4, or the pumps have run for a predetermined length of time. The blood pump will then be reversed to empty fill tube 24, which allows this tube to be clamped and disconnected from the y-connector. A second process bag tube can then be connected to the y-connector and the above process repeated for the second bag.

Red Cell Sedimentation: At this point, the process bag contains a mixture of blood and starch fluid. The starch causes the red blood cells to agglomerate in the process known as rouleaux, and the agglomerations of cells fall under the forces of gravity to settle on the lower interior surface of the bag 12, which is supported in the desired orientation by the surfaces 14. Because the bag 12 is constrained between the surfaces 14 and 16, which are spaced by about 1.15 inch, the maximum distance through which the cells must fall before reaching the lower surface of the bag is less than two inches, i.e., about 1¾ inch. The agglomerations fall through that distance in a short period of time and then slide even more quickly down to the bottom to the outlet in an avalanche. The array 48 of light detectors monitors the blood-starch mixture and determines the position of the meniscus that forms between the upper layer of reduced

hematocrit and the lower layer of increased hematocrit resulting from the increased concentration of red blood cells in the lower part of the bag. The upper layer then contains the plasma, saline, and any surgical debris.

Transfer of Red Blood Cells: During installation of the process bag, the drain line 40 is secured in the drain control 42, which is normally closed to retain the fluids in the process bag until sedimentation is completed.

The determination of when to open the drain control valve to discharge the red blood cells may be done in any of several ways, as described above. Preferably, the position of the meniscus is used to confirm that a proper sedimentation has occurred. That is, movement of the meniscus a predetermined distance in a predetermined time indicates that proper separation has occurred, and the drain is opened to discharge the red blood cells. The particular times and distances will depend on the particular apparatus and can be empirically determined.

It has been found in practice that the hematocrit tends to be reduced toward the end of a drain cycle. Thus, in the preferred operation, the drain control valve is modulated (i.e., cyclically opened and closed) toward the end of the drain cycle to reduce the drain speed to maintain the hematocrit.

The sensor 44 determines the hematocrit of the draining fluids. Signals from this sensor are provided to the PLC, and the drain valve will be closed to terminate the draining if the hematocrit is too low, e.g., less than 35%. The PLC will then wait for a period of time before again opening the drain valve. That period of time can be fixed or it can be determined as a function of various factors, such as the volume of blood remaining in the process bag.

We Claim:

1. Apparatus for facilitating gravity separation of a first substance from a second substance comprising a first plurality of surfaces arranged about a vertical axis and tapering to a common location on said axis, and a second plurality of surfaces arranged about said vertical axis and tapering to a second common location on said axis, wherein said second plurality of surfaces is spaced from said first plurality of surfaces in the direction of said axis to form a channel therebetween for receiving a mixture of said first and second substances for gravity separation.
2. Apparatus according to claim 1 further wherein each of said first and second plurality of surfaces is triangular.
3. Apparatus according to claim 1 further comprising a support for holding said first and second plurality of surfaces at a predetermined angle of between 40° and 70° with respect to the horizontal.
4. Apparatus according to claim 3 wherein said predetermined angle is 55°.
5. Apparatus according to claim 3 further comprising at least one pump for supplying a mixture of said first and second substances to said channel.
6. Apparatus according to claim 5 further comprising a drain valve at said common location for discharging said first substance from said channel after said separation.
7. Apparatus according to claim 6 further comprising a control system for activating said pump and controlling said drain valve.
8. Apparatus according to claim 7 wherein said control system comprises an array of detectors capable of detecting the location of the boundary between said furst and second substances.

9. Apparatus according to claim 7 further comprising a flexible bag shaped to fit in said channel, said pump is connected to said flexible bag said first substance is red blood cells, and said second substance is starch.

10. Apparatus comprising a base having a channel therein, said channel being of constant depth in one direction and triangular in a transverse direction, and said slot extending in said transverse direction at a predetermined angle with respect to the horizon, and a flexible bag removably placed in said slot.

11. Apparatus according to claim 10 wherein said flexible bag includes a drain outlet and is filled with red blood cells and starch, whereby red blood cells separated from said starch accumulate adjacent said drain.

12. In combination, a flexible bag having upper and lower surfaces and a perimeter and being shaped to fit within a slot defined by a first plurality of surfaces arranged about a vertical axis and tapering to a common location on said axis, and a second plurality of surfaces arranged about said vertical axis and tapering to a second common location on said axis, wherein said second plurality of surfaces is spaced from said first plurality of surfaces in the direction of said axis.

13. A combination according to claim 12 in combination with a fill tube, a drain tube and a second flexible bag attached to said drain tube.

14. A method for separating red blood cells from other fluids comprising supplying said red blood cells to a container, adding a substance to said red blood cells to encourage formation of agglomerations of said red blood cells, allowing said agglomerations to separate from said substance by gravity, automatically sensing

the position of a boundary between said agglomerations and said substance, and opening a drain valve on said container.

15. A method according to claim 14 wherein said substance is starch.

16. A method according to claim wherein said container is a flexible bag removably supported in a slot formed between two spaced surfaces.

FIG. 1

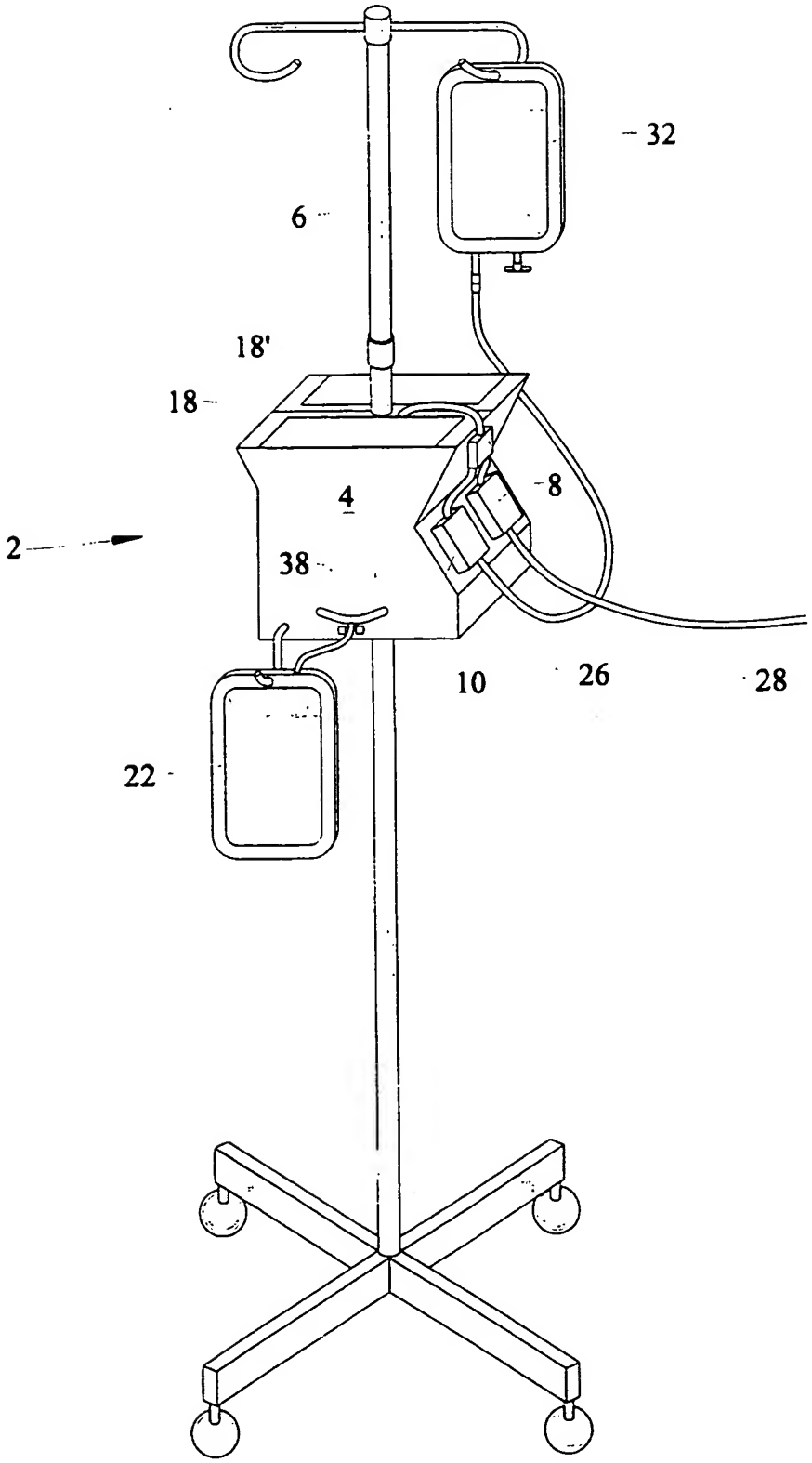


FIG. 1A

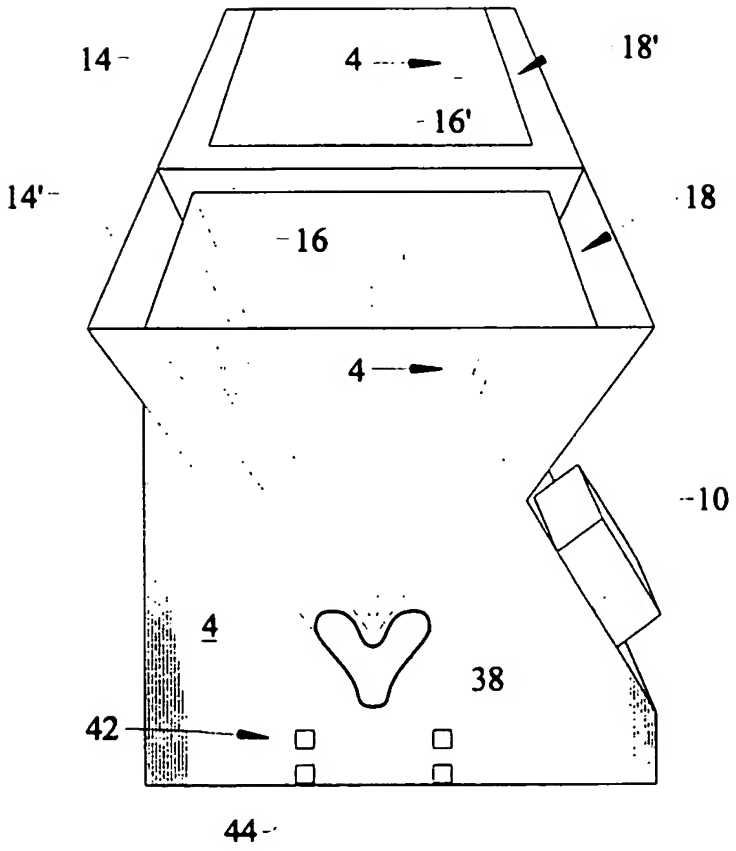


FIG. 2

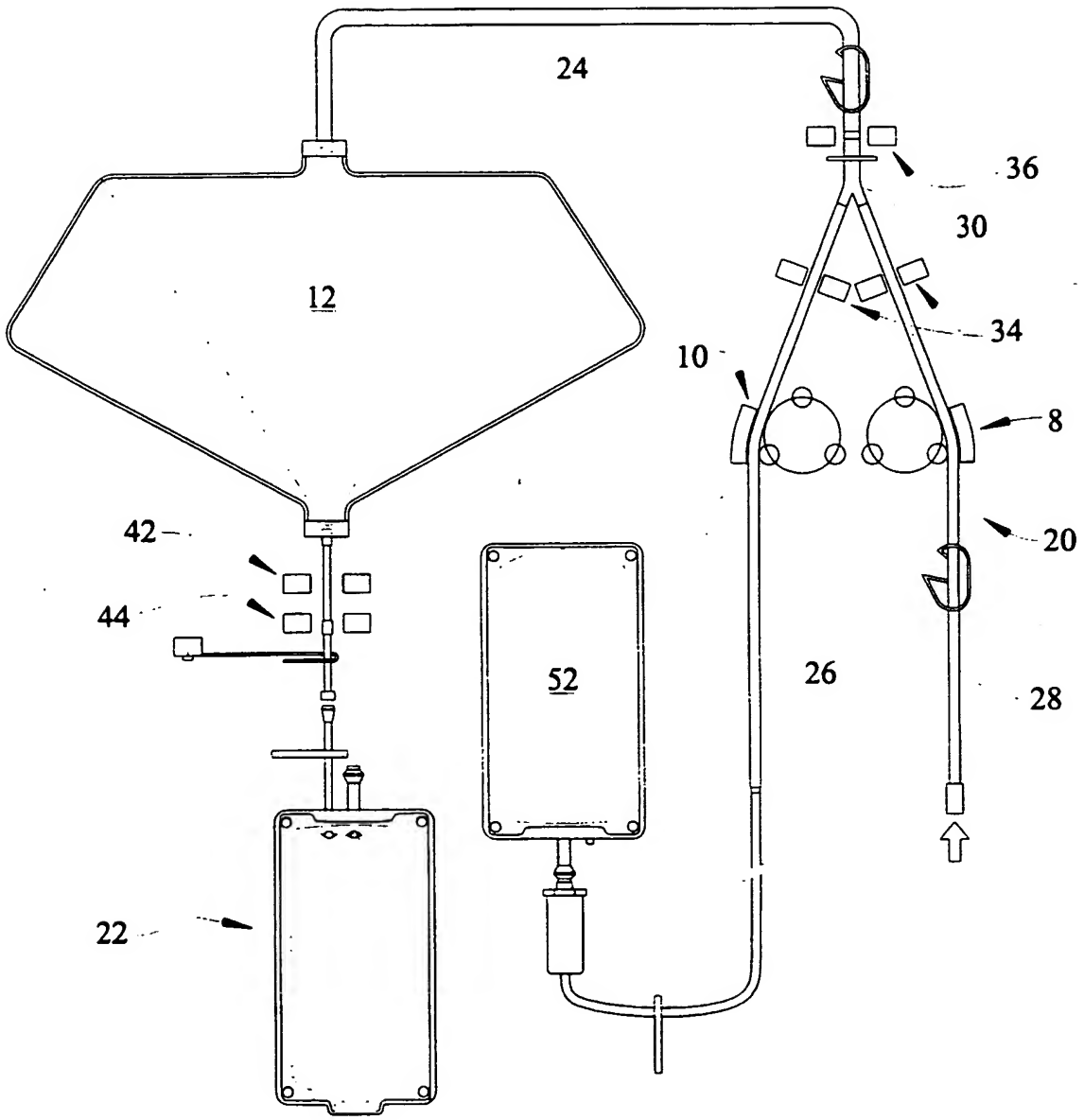


FIG. 3

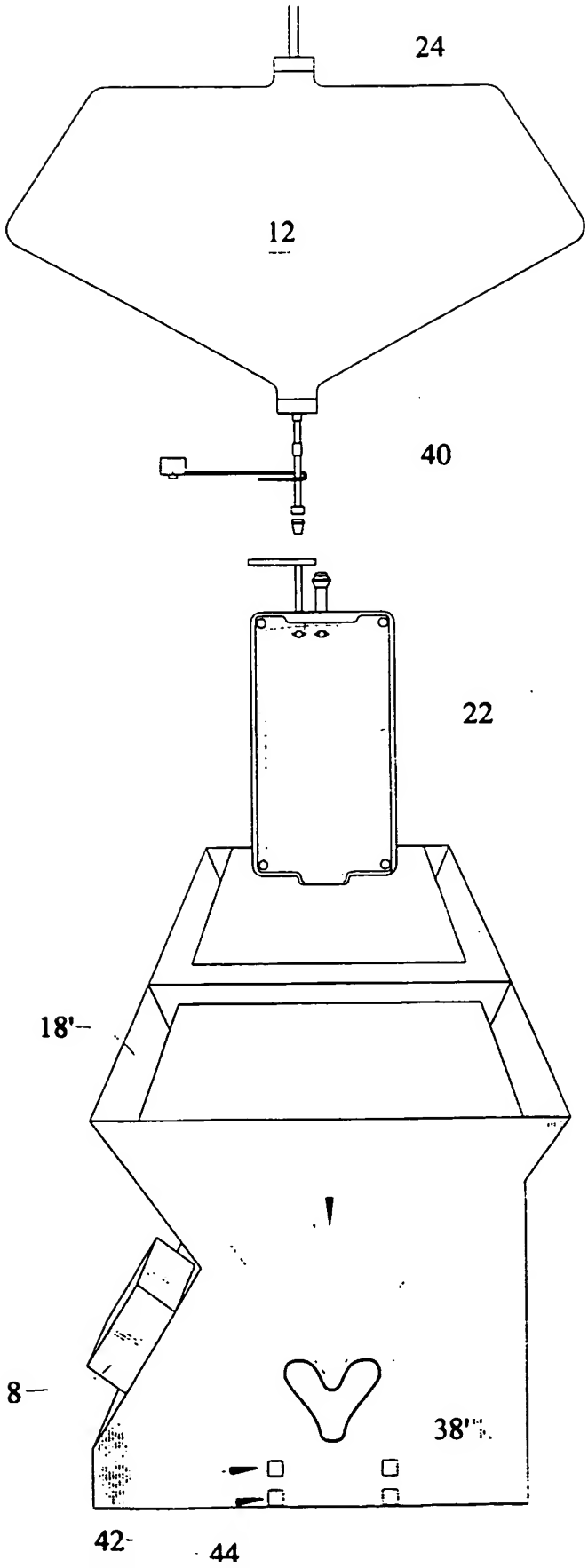


FIG. 4

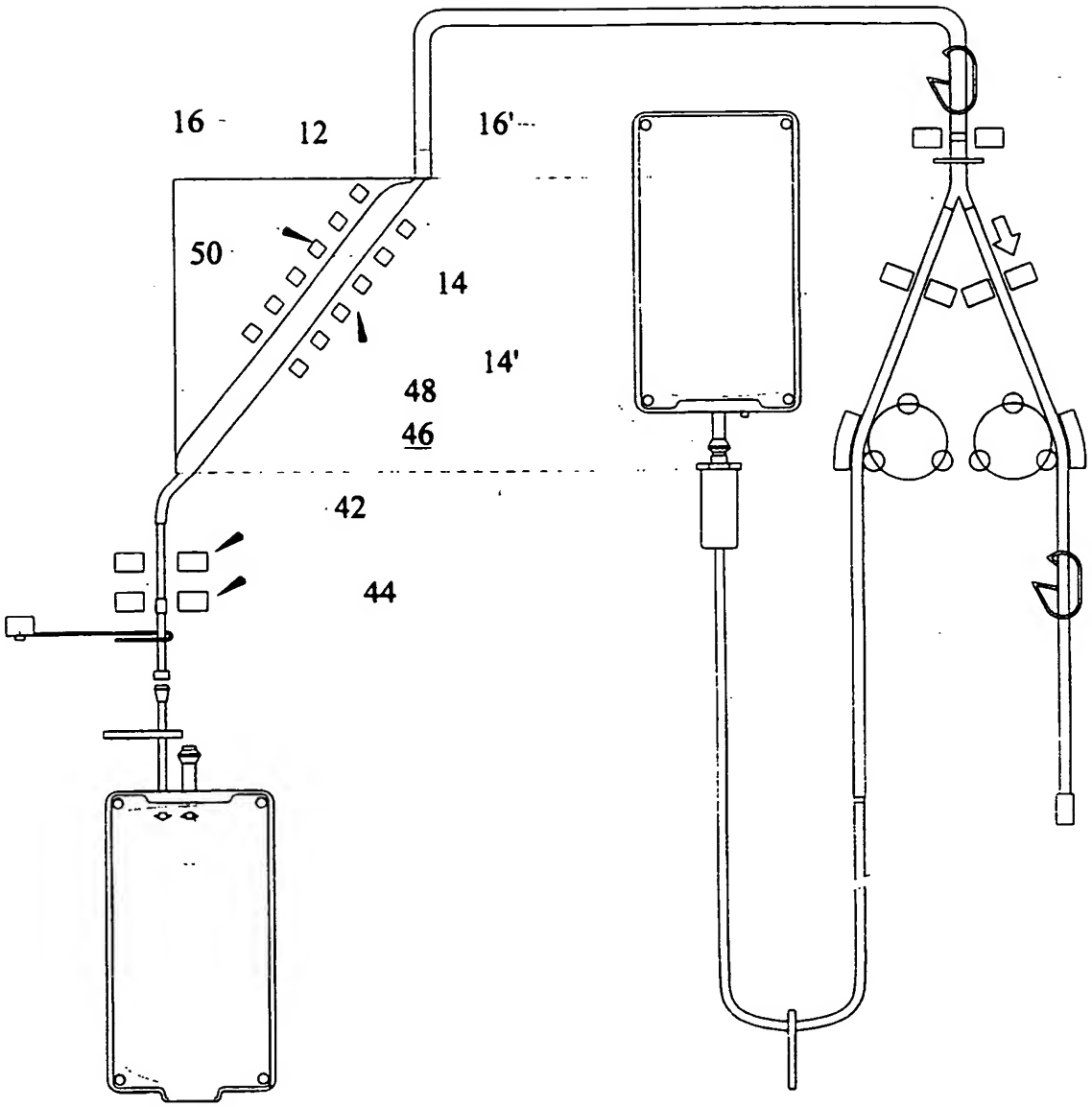
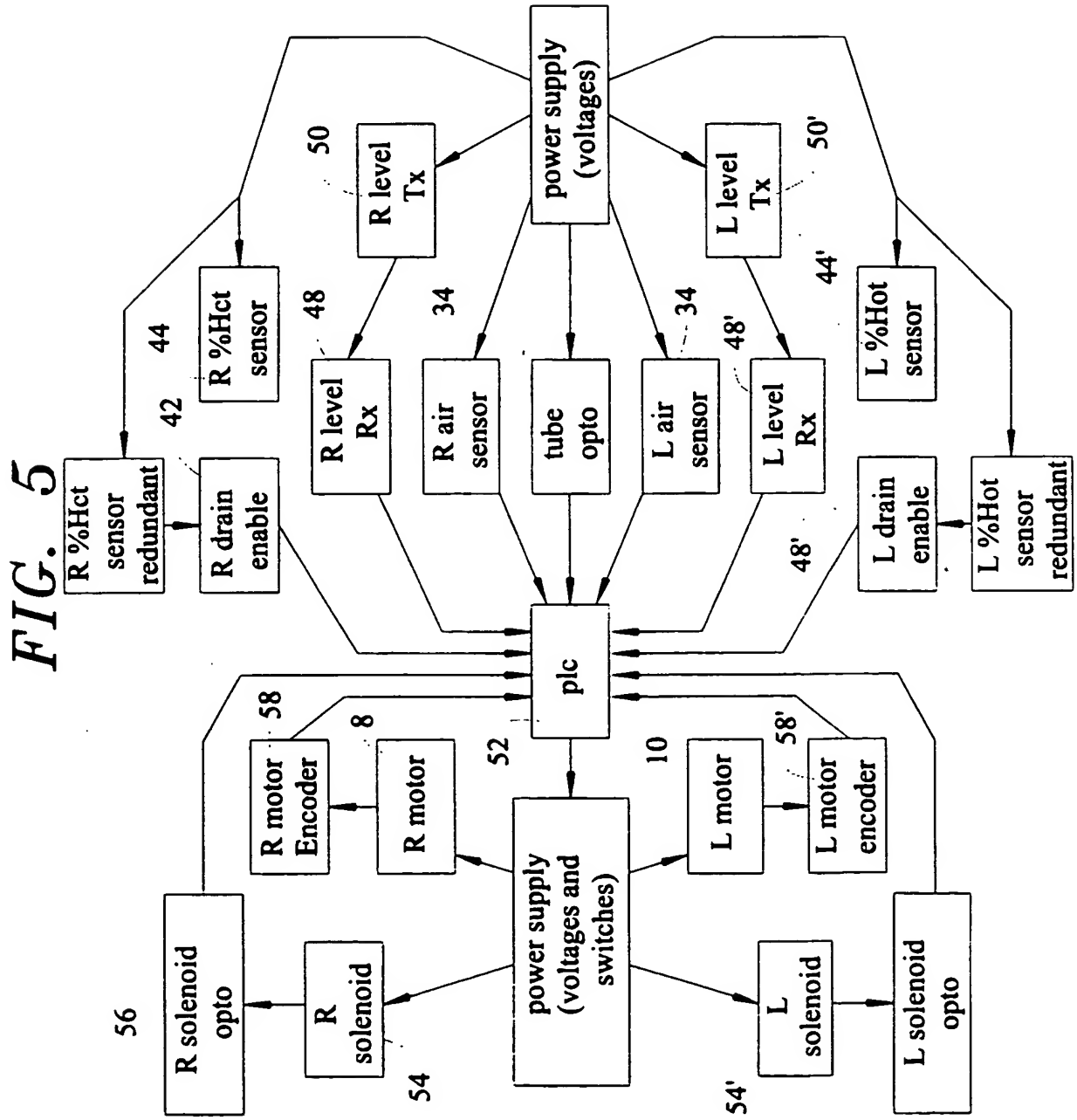


FIG. 5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R level Tx
L level Tx
50
50'
R %Hct sensor
L %Hot sensor
44
44'
42
R level Rx
R air sensor
tube opto
L air sensor
L level Rx
48
34
34
48'
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R drain enable
L drain enable
L %Hot sensor redundant
48'
plc
58
58'
8
10
52
R motor Encoder
R motor
L motor
L motor encoder
power supply (voltages and switches)
R solenoid opto
R solenoid
L solenoid
L solenoid opto
56
54
54'